



ILC Beam Delivery WG Summary: Optics, Collimation and Background*

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Abstract

The paper summarizes the work of the Beam Delivery working group (WG4) at Snowmass 2005 workshop, focusing on status of optics, layout, collimation and detector background. The strawman layout with two interaction regions was recommended at the first ILC workshop at KEK in November'04. Two crossing-angle designs were included in this layout. The design of the ILC BDS has evolved since the first ILC workshop. The progress on the BDS design including the collimation system, and extraction line design have been reviewed and the design issues were discussed during the WG4 sessions at the Snowmass, and are described in this paper.

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The presented paper partially summarizes the work of the Beam Delivery working group (WG4) at Snowmass, concentrating on status of optics, layout, collimation, and background. The strawman layout with 2 interaction regions was recommended at the first ILC workshop at KEK in November'04. Two crossing-angle designs were included in this layout. The design of the ILC BDS has evolved since the first ILC workshop. The progress on the BDS design and extraction line design has been reviewed and the design issues were discussed during the optics and layout session at the Snowmass.

1. INTRODUCTION

The tentative strawman configuration recommended by the Beam Delivery System working group during first ILC workshop [1] was the working hypothesis for the BDS design. The ILC beam delivery system is being designed by an active international group. Several critical assumptions, which are beyond the scope of the BDS group, have been adopted for this baseline design. To follow the recommendations of the particle physicists and to provide a complementary physics program at the two interaction regions (IR), two IRs are recommended. One of the interaction regions has a large crossing angle, providing possibility of gamma-gamma collisions while the other IR has a very small crossing angle, providing advantages of almost head-on collisions. The upstream optics of both the beam delivery systems, namely, transporting the beam to the large and small crossing angle regions, has been worked out in details. The working group discussed the design progress and issues of the lattice design for both the beam delivery systems and the extraction lines.

2. BEAM DELIVERY SYSTEM LAYOUT

2.1. Layout and sequence of beam line

The recommended “strawman” layout at the time of the first ILC workshop is shown in Fig. 1. Since the workshop, the BDS design has progressed significantly. This configuration required development of the complete optics design. This included completing the optics design for both IRs with all beam diagnostics, design of extraction lines and passing of decks for evaluating the physics impact on optimization of IR parameters. The optics layout of the present design is shown in Fig. 2. The beam line sequence starting from the linac exit consists of: beam coupling correction section, beam emittance measurement section, fast extraction and tune-up beam line, beam switchyard (for switching the beam to 2-mrad crossing angle IR), polarimeter, betatron collimation, energy collimation, energy spectrometer, final

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focus with tail folding octupoles, final doublet, interaction point, extraction beam lines including energy and polarization diagnostics and beam dumps.

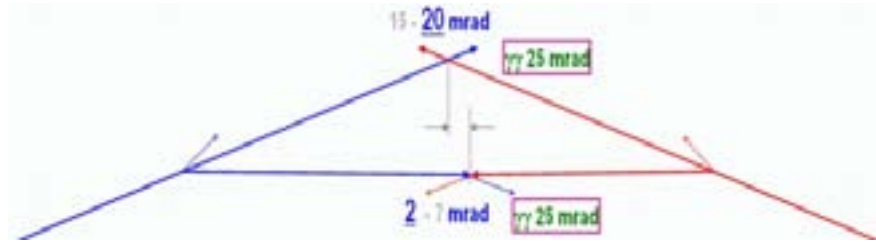


Figure 1: Tentative working hypothesis, strawman configuration recommended by WG4 at 1st ILC workshop

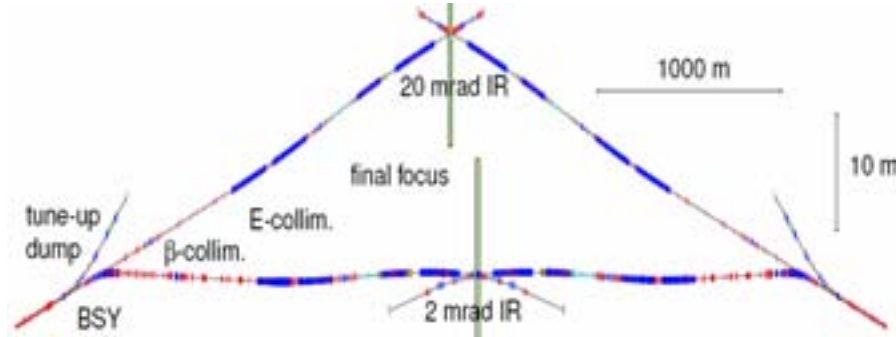


Figure 2: Layout of the present ILC BDS

2.2. Beam diagnostics section and fast extraction

The coupling correction at the beginning of the beam delivery system is designed to correct the cross-plane coupling in order to prevent dilution of the very low emittance achieved in the damping rings. The coupling correction scheme and the 2D emittance measurement section proposed for the NLC [2] has been incorporated into the ILC BDS. The present scheme has tuning and fast extraction line at the end of this section. The optics of this part of the line is shown in Fig. 3. In commissioning/tuning mode, DC magnets will be switched on to divert the beam to this dump line. One of the options to provide the signal fast extraction is to use the downstream machine protection BPM located at the energy collimation section. The sequence of beam kicker and BPM allows double the number of bunches compared to the BPM and the kicker case. Since in this scheme the energy errors will be detected at the energy collimator located ~600 m downstream, about 30 bunches will pass through the system taking into account the bunch spacing of 150 nsec at 1 TeV. Detection of off-energy bunches at the polarimeter chicane would allow up to 10 bunches to pass through the BDS. As the survivable betatron spoilers can survive up to 2 bunches @500 GeV CM and only one bunch@1TeV CM, and energy spoiler is just slightly more safe, these options will not be acceptable as the energy spoiler will not survive such a large number of bunches and BDS components and the detector may be harmed.

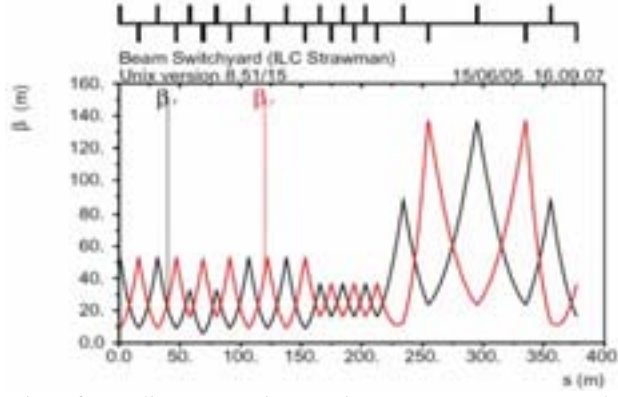


Figure 3: Optics of coupling correction, emittance measurement and fast extraction

As it is proposed to use laser wires to measure the beam profiles in the beam emittance section, some kind of bending is required to separate out the Compton scattered photons. So, considering the requirement of detecting the off-energy beams at the nearest point after the beam diagnostics section, the group discussed and proposed to incorporate a chicane after the beam emittance section to be followed by the extraction kickers/DC magnets. The laser wire signal can also be detected with this chicane leaving necessary clearance in the magnets.

The vertical beam sizes at the laser wire locations in the emittance measurement optics are around $1 \mu\text{m}$, which can be measured using laser wires with $\sim 10\%$ accuracy [3]. To improve the accuracy, the beam sizes need to be increased to $\sim 3 \mu\text{m}$ which will require significant increase in the length of the beam emittance section. The group suggested to carry out performance studies to be able to decide whether a 10% accuracy would be good enough.

2.3. Fast extraction and tune-up beam line

The present design of fast extraction and tune-up line [4] has $\pm 20\%$ energy acceptance and the line uses non-linear elements to minimize the beam size and position variation at the beam dump when energy is changed. The on-energy beam sizes onto the beam dump are shown in Fig. 4. Recent estimates for the beam sizes on the dump window [5] indicate that the beam sizes will need to be increased further and sweeping of beam needs to be included in the design. The required acceptance for the beam is the necessary input for this line. The tune-up dump is assumed to take full power of the beam.

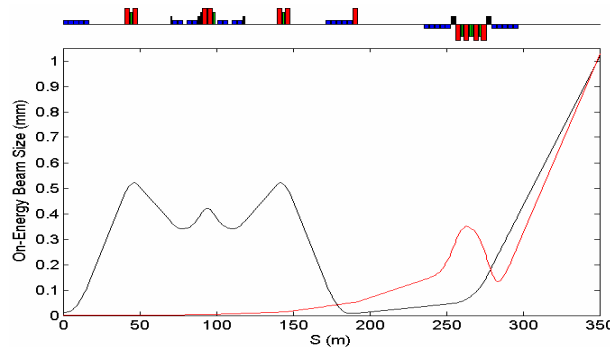


Figure 4: Optics of fast extraction/tune-up line

2.4. Collimation and final focus optics

The collimation optics and the sequence of betatron and energy collimation are similar to that of the NLC design. The beam sizes at the spoilers have been increased to make the spoiler survivable. The beam sizes at the spoiler locations will survive up to 1-2 bunches on the betatron spoilers. The performance of this scheme has been reported in the collimation section [22]. The final focus system is based on the local chromaticity correction scheme like that was proposed for the NLC. The system has very good chromatic properties with a large bandwidth. The optics for collimation and final focus is shown in Fig. 5. The geometric and chromatic aberrations are minimized up to the fourth order. The optics of the final focus and the collimation has been optimized to obtain a good bandwidth for the design. The tail-folding octupoles are off in the present lattice and show a good tail-folding when on. The design has been optimized for the 20-mrad BDS, and the preliminary design for 2 mrad is encouraging [7]. First results indicate that it is possible to optimize the optics to get a similar performance like for the 20-mrad final focus. Present designs are for L^* of 3.5m for the 20-mrad case and for L^* of 4.5m for the case of 2 mrad. The team plans to provide the designs for L^* in the range of 3.5m to 5m.

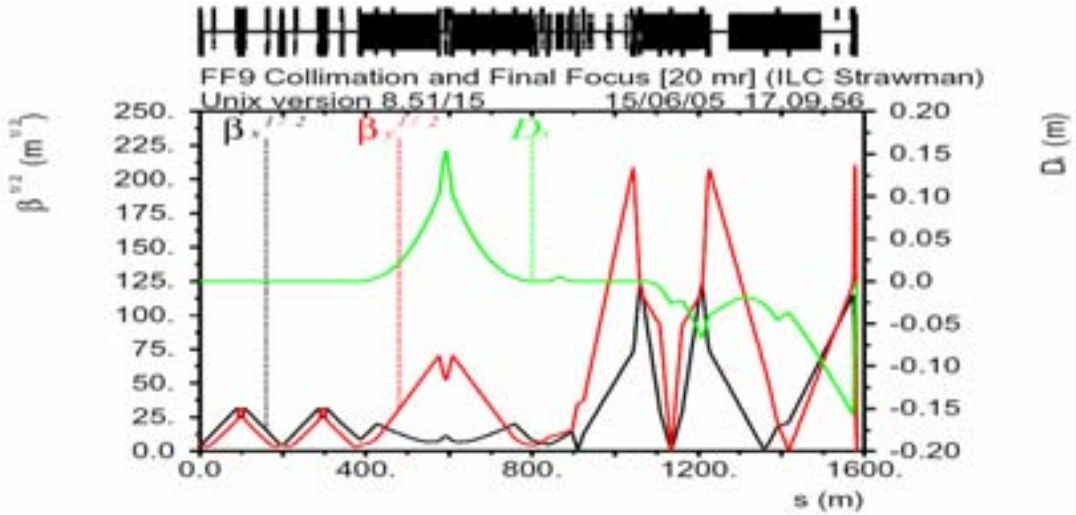


Figure 5: Collimation and final focus optics for 20 mrad

2.5. Big bend for 2 mrad

In the strawman configuration, it is necessary to bend the beam by 11 mrad in order to get a 2-mrad total crossing angle at the IP. The lattice shown in Fig. 6 has been optimized [4] to keep the emittance growth due to incoherent synchrotron radiation to minimum. A chosen combined function dipoles and FODO lattice gives an emittance growth of 11% @1 TeV CM. The group discussed the necessity of working out the engineering details and tolerance requirements of these magnets. Other lattices may also be studied to compare.

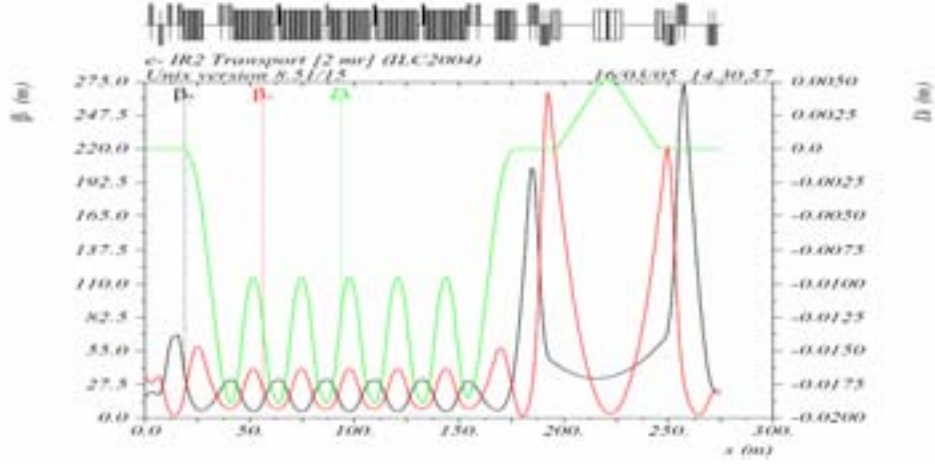


Figure 6: Optics of big bend for 2 mrad IR

2.6. Upstream energy spectrometer and polarimeter chicanes

Energy spectrometer chicane has been included in this lattice. The emittance increase due to ISR is less than 0.075% at the 1-TeV CM energy. The group expressed the need to discuss the detailed scenario of ramping this chicane for different energy operations. The total length required for this chicane is around 50 m. A polarimeter chicane has also been incorporated into the lattice and the emittance growth due to ISR is less than 0.07% for this chicane as well. The length required is about 55m for this chicane.

2.7. Detector-Integrated Dipole (DID) and antisolenoids

In case of a large crossing angle, the beam traverses the magnetic field of the detector at an angle and thus will be deflected into the vertical plane. The change in the vertical orbit causes degradation of the beam size due to synchrotron radiation and also causes rotation of the polarization vector if the total vertical angle is non zero. These effects were studied in details for the NLC. Local compensation using a novel dipole coil integrated with the detector has been found to be an effective way for both e+e- and e-e- beams [8]. The DID has also been suggested for the ILC in case of a 20-mrad crossing angle. As reported in [9], the background in the TPC increases in presence of this field. The group discussed the case that if DID is not used and final doublet was offset to cancel both IP offset and angle, the beam size growth due to SR was tolerable only if one would abandon the constraint of the IP position w.r.to beam line [10], then offsetting QD0 makes it possible to compensate the IP angle. The present studies have been carried out for SiD with $L^*=3.5\text{m}$ and need to be repeated for other detectors and other L^* .

2.8. 20-mrad extraction line optics

The 20-mrad optics is based on the independent beamline for the spent beams [11], without sharing the final focus magnets. The outgoing primary beam and the beamstrahlung photons are transported through the same extraction

magnets to a common beam dump. The optics of this line consists of the DFDF quadrupoles followed by two vertical diagnostics chicanes and two protection collimators before the dump. The optics of the 20-mrad line is shown in Fig. 7. With same L^* of 3.5m for both the incoming and extraction lines, the compact superconducting quadrupole designs also provide an advantage of compensating the residual field of QD0. The losses in this line have been estimated using both DIMAD and STRUCT [12] for different parameter sets. The losses on the magnets are within acceptable limits for the nominal parameter sets [13] and acceptable at high luminosity parameters @500GeV CM.

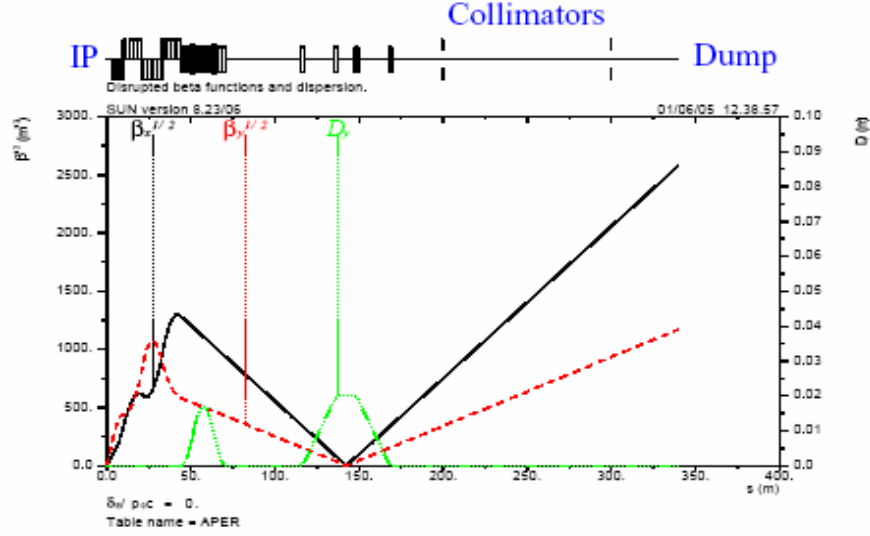


Figure 7: Optics for 20-mrad extraction line

2.9. 2-mrad extraction line optics

Several versions of optics have been designed since the first ILC workshop. Comparison of short and long doublets considering the losses in the final doublet (FD) and along the line, and collimation depths were evaluated for these designs. In order to maximize the energy bandwidth of the extraction optics, the FD has been optimized to simultaneously satisfy both the incoming and extraction optics requirements. Fig. 8 shows the beam envelopes in the horizontal plane including low-energy tail particles using TURTLE tracking. A SC QD0 with radius of 35mm has been considered for this design. The extracted beam also passes off-centered on the final focus sextupoles and thus large bore designs are required for these sextupoles. The optics design of this line [14] has an energy clean-up chicane in the vertical plane, followed by the energy spectrometry and polarimetry chicanes. Dedicated collimation sections have been provided to control the beam loss. The losses in the 2-mrad line estimated using STRUCT [12] show unacceptable beam losses at high luminosity parameters @500 GeV CM. The group will continue to optimize the design of this line.

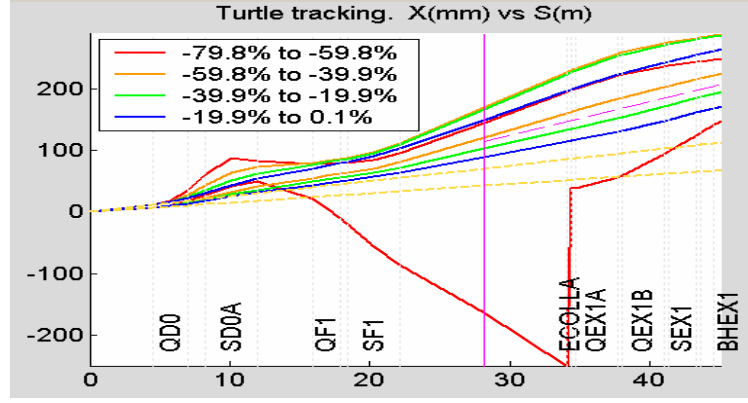


Figure 8: Tracking of extracted beam in 2-mrad IR

From the incoming and extraction point of view, it is also possible to use this interaction region for e-e- [15]. The optics constraints require reversing polarity of the FD and thus increasing β_y^* by about a factor of 30. This will require retuning for the incoming final focus optics. It is possible to achieve e-e- luminosity which will be 8% of that of the e+e-. But increasing the vertical size is also beneficial for the feedback and can also be done for the 20-mrad IR.

2.10. Zero-degree extraction

The head-on scheme proposed for TESLA had a number of problems identified by the TRC study [16]. The head-on scheme has been recently reconsidered with attempts to improve it. In one case, the electrostatic separator was suggested to be replaced by an RF-kicker [17], which, however, introduced severe MPS concerns and other issues. In another case, the extraction optics was modified so that the kick required from electrostatic separator was reduced [18], improving its feasibility even at 1 TeV CM. These options will be explored in near future to see the feasibility and worked out in details. The working group discussed the design progress and issues of the lattice design for both the beam delivery systems and the extraction lines.

3. COLLIMATION AND BACKGROUND

The current design of the betatron and energy collimation scheme for the ILC BDS is based largely on that of the NLC, developed some years previously and described in [19,20]. The scheme is the same in both 20-mrad and 2-mrad crossing angle lattices, and consists of a betatron collimation section followed by energy collimators. This way degraded energy particles originating from betatron collimation section (and not absorbed there) may be collected by the energy collimator. The collimation system [21] consists of spoiler/absorber pairs, arranged to survive impact from errant bunches which escape the machine protection fast extraction system. Additional protection collimators are located elsewhere in the BDS providing local protection of components and absorption of scattered halo particles, while synchrotron radiation masks in the immediate vicinity of the interaction point (IP) protect collider detector components. The baseline design involves spoilers which would survive impact by errant bunches that escape the machine protection system. The current status of collimation-related research was summarized in [22].

Collimation depths for the current lattice designs are primarily determined by clearance of final-doublet synchrotron radiation through the interaction region. This has been studied using both linear optics calculations [22] and more

advanced simulations [23]. Collimation depths are sensitive to IR geometry and machine parameters (emittance, IP beta-functions). The IR geometry is very different in the 20-mrad and 2-mrad lattices. In the 20-mrad case, the limiting aperture is the first extraction quadrupole; in the 2-mrad case, the beam calorimeter and the extraction pocket of the final focusing quadrupole impose the constraints. In addition to radiation fan clearance, another possible constraint may arise from the halo acceptance of the final quadrupoles, where the horizontal beam size is very large at $\sim 1\text{mm}$. From the results presented, general values of the collimation depths summarized as $\sim 10\sigma_x$ and $\sim 50\text{--}80\sigma_y$, as in previous linear collider lattice designs [24].

The performance of the collimation system in the 20-mrad case has been studied with halo tracking simulations, similar to those described in [20]. These assume an initial halo distribution from the linac exit filling a large region of phase space, and measure the collimation efficiency and halo related losses along the beam-line. From these studies, it is evident that some halo escapes the collimated phase space between the betatron spoilers and the final doublet, particularly in the horizontal plane. This can be remediated by setting narrower spoiler apertures, and using the energy spoiler as a secondary betatron spoiler; in addition a better optimization of the beam optics of the collimation system with respect to the final doublet would be beneficial.

The survival of the collimators in the case of errant beams has been examined in previous studies [25]. Extrapolated to the 20-mrad deck, where the beam size is $\sim 1000\text{ }\mu\text{m}^2$ at the betatron spoilers, the results indicate the spoilers can survive at most two errant bunches at 500 GeV center-of-mass, and only one at 1 TeV. This places very tight constraints on the machine protection and fast extraction system.

The studies of the dynamic heat load show that most of energy among the beam line elements is deposited in the protection collimators PC1, PC5, PC8 and PC9 [26]. Residual activation and radiation damage in the magnets downstream of those is in excess of the limits if the length of the PCs is kept $15 X_0$ as originally proposed. For example, an average residual dose on-contact after 30 days of irradiation and one day of cooling on the front surface of the first quadrupole downstream of PC1 is as high as 7.7 mSv/hr compared to the limit of 1 mSv/hr. The absorbed dose in quadrupole coils reaches 300 MGy/yr compared to the coil insulation limit of about 4 MGy, meaning a lifetime of only a few days. This forced one to increase the PC's length to $45 X_0$ (about 60 cm of copper) resulting in the coil lifetime of at least several years [27]. Dynamic heat load distribution obtained with the MARS15 code after the collimator optimization gives acceptable loads for magnets, about 50 W/m for spoilers, and about 10 kW/m for the protection collimators PC1, PC5, PC8 and PC9.

Wakefield effects in the current lattices and for current collimation depths so far have not been examined thoroughly, however they may be significant, as previous research has shown [28]. A program of collimator wakefield measurements has been proposed at the SLAC end station A, to begin before the end of 2005, which will help to optimize the design spoiler geometry and improve wakefield prediction techniques. The extent of spoiler damage by errant beams may also be studied.

MARS15 simulations confirm that synchrotron photons produced from the beam core and halo upstream of the IP are collimated by the photon masks and - with an appropriate design - their contribution to backgrounds and radiation loads to extraction line components is negligible. Same applies to beamstrahlung photons which form a very narrow beam. e+e- pairs and synchrotron photons generated by disrupted beam remain the main source of the IP backgrounds and radiation loads to detector, final focus and extraction components [26]. At high luminosity and 120-nm vertical offset,

the total radiation load in the extraction beam line is 13.3 kW with a 600 W/m peak [29]. Without a vertical offset, these numbers are a factor of ten lower. This is to be compared to estimated tolerance levels of 10 W/m for superconducting magnets and a few hundred W/m for conventional magnets [26].

The current status of backgrounds studies in the ILC detectors was summarized in [26] both for the IP- and BDS-generated components. There is a substantial progress both in simulation package development and background studies in all three regions: Europe, Japan and USA. Sources studied for the collision point include e+e- pairs, disrupted primary beam, beamstrahlung photons, radiative Bhabas and hadrons from $\gamma\gamma$ interactions. In general, these sources are well understood and under control, although there is a significant sensitivity to the ILC and machine-detector interface parameters. For example, a background hit rate density in the vertex detector pixels is 10 times higher for 1-TeV collisions at high luminosity compared to 0.5-TeV collisions at nominal luminosity in a low-Q case. Including in modeling realistic magnetic fields for the detector solenoid and detector integrated dipole can increase the hit rate in the TPC by up to a factor of ten compared to an ideal field configuration [30].

Beam-line backgrounds include synchrotron radiation, spray from the extraction lines, beam-gas and beam halo interactions with collimators and other components in BDIR which create intense fluxes of penetrating particles at the collider detector. The main concern here is muons, predominantly the Bethe-Heitler pairs, created in electromagnetic showers. Fluxes of these muons accompanied by other secondaries, could exceed the tolerable levels at the detector by a few orders of magnitude [26]. Calculated with the MARS15 code muon flux equals to $4.1 \text{ cm}^{-2} \text{ s}^{-1}$, or 7600 muons in the tunnel aperture for 150 bunches from one beam. This is to be compared to a few muons allowed in such a sensitivity window. The mean energy of these muons is about 27 GeV. About 700000 photons and 200000 electrons accompany these muons at the detector. The fluxes double for energetic muons for two beams.

Magnetized spoilers sealing the tunnel would reduce muon fluxes substantially (as proposed by L. Keller earlier). MARS15 calculations were performed for two iron spoilers 9- and 18-m thick at 648 and 331 m from the IP, respectively. The square spoilers are extended by 0.6 m in the tunnel walls and dirt on each side. The field of 1.5 T is used in opposite polarity on left and right sides to compensate it at the beam pipe center. Central gaps are 10-cm wide and 1-m high with a 0.8-T field. The gap between the parts is as the beam pipe. This set of spoilers reduces the muon background load on the detector from 7600 to 2.2, i.e. to about the acceptable level. Other particle fluxes coming from the tunnel are also down in about the same proportion. Two alternatives to the muon tunnel spoilers need to be investigated: muon attenuator (about 120-m long collar with 1-T field, 0.6-m OD) and wide-aperture magnets.

Future important research topics include:

- A closer study of the use of octupole doublets for beam tail-folding, which may ease the constraints of the collimation system considerably.
- Generation of a table of tolerable beam losses and radiation loads on superconducting and conventional magnets.
- Further reduction of radiation loads to the BDS and extraction line components at normal operation and beam accidents.
- Building consistent, realistic BDS+detector integrated models, with detailed magnetic field maps, tunnel and experimental halls.
- Adding engineering realism wherever possible.
- Generation of sub-detector tolerance tables on three levels: (1) pile-up; (2) pattern recognition; (3) radiation damage.
- Study backgrounds for three detector concepts and two crossing angles: (1) sensitivity windows with respect to a tagged origin and bunch crossing; (2) tag origin of backgrounds for all particle types; (3) further explore

mitigation methods such as better collimation performance, low-Z masks, muon tunnel spoilers, attenuators or wide-aperture magnets.

- Code/model benchmarking; interfacing.
- BDIR code/model/map depository.

Acknowledgments

This paper describes the status of the beam delivery system design for the ILC, namely optics, layout, collimation and background. The authors wish to thank to all the colleagues working on the BDS design and the WG4 members.

References

- [1] First ILC workshop, KEK, November 2004
- [2] M. Woodley, P. Emma, "Measurement and correction of cross-plane coupling in transport lines", Linac 2000, August 2000.
- [3] G.Blair, "ILC Laser wires", Snowmass 2005, August 2005.
- [4] M. Woodley, "ILC strawman design : beam switchyard, tune up dump, diagnostics", BDIR workshop, 2005.
- [5] D.Walz, "Beam dump concept for ILC", Snowmass 2005, August 2005
- [7] A.Seryi, "FF optics for 2mrad with $L^*=4.5\text{m}$ ", SLAC BDS meeting, August 2005
- [8] B.Parker, A.Seryi, DID, <http://prst-ab.aps.org/abstract/PRSTAB/v8/i4/e041001>
- [9] K.Buesser, "Pair backgrounds in the Large Detector", BDIR Workshop, June 2005.
- [10] V.Telnov, LCWS05?
- [11] Y.Nosochkov, "20 mrad extraction line", Snowmass 2005
- [12] A.Drozhdin, "STRUCT Modeling of Collimation and Extraction System Performance", BDIR Workshop, London, June 2005
- [13] T. Raubenheimer, "ILC suggested Beam Parameters Range", SLAC-, February 2005
- [14] Y. Noshochkov, "2 mrad extraction line design", Snowmass 2005
- [15] A.Seryi, "e-e- in 2mrad optics", SLAC BDS meeting, August 2005.
- [16] Report of 2nd ILC Technical Review Committee, SLAC-R-606, Feb 2003.
- [17] Y. Iwashita, "Update on rf kicker 0-degree scheme", Snowmass 2005
- [18] L. Keller, "Zero-degree extraction with an electrostatic separator", Snowmass 2005
- [19] NLC Technical Note LCC-0052. New Post-Linac Collimation System for the Next Linear Collider," P. Tenenbaum, Contact for New Post-Linac Collimation Collaboration, 02/01.(SLACTN-03-069)
- [20] NLC Technical Note LCC-0111. "Comparison of the TESLA, NLC and CLIC Beam Collimation Systems," A. Drozhdin et al. January 2003.(SLAC-TN-03-003)
- [21] N.V. Mokhov et al., "Beam Collimation and Machine-Detector Interface at the International Linear Collider", PAC2005 paper, Fermilab-Conf-05-154 (2005)
<http://www-ap.fnal.gov/users/mokhov/papers/2005/Conf-05-154.pdf>
- [22] Presented by F. Jackson
http://alcp2005.colorado.edu/alcp2005/program/accelerator/WG4/aug16_collimation_summary_jackson_snow05.ppt
- [23] Presented by J. Carter
http://alcp2005.colorado.edu/alcp2005/program/accelerator/WG4/aug16_carter_Snowmass05_CollDepth.pdf
- [24] Beam Delivery System for Pedestrians, N.Walker, 26th Advanced ICFA Beam Dynamics Workshop, 2002
- [25] Presented by L. Keller at ILC Americas Workshop
<http://www-project.slac.stanford.edu/ilc/meetings/workshops/US-ILCWorkshop/workshop.html>
- [26] Presented by N.V. Mokhov
http://alcp2005.colorado.edu:8080/alcp2005/program/accelerator/WG4/aug16_mokhov-bg-snow05.ppt
- [27] Presented by M.A. Kostin
http://www-project.slac.stanford.edu/lc/bdir/Meetings/beamdelivery/2005-06-16/index.htm/kostin_050616.pdf
- [28] Second ILC-Technical Review (Section 7.3.2.6, p340) <http://lcdev.kek.jp/TRCII/>
- [29] Presented by M.A. Kostin
http://www-project.slac.stanford.edu/lc/bdir/Meetings/beamdelivery/2005-07-19/index.htm/MKostin_July19.pdf
- [30] Presented by K. Busser
http://alcp2005.colorado.edu:8080/alcp2005/program/accelerator/WG4/aug16_buesser_pairs.ppt